Optimal recovery paths in a metapopulation

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Outline

- Introduction
- Economic-ecological metapopulation model
- Some numerical results on recovery paths
- Concluding remarks

Designing recovery plans

- Notable declines in some (very) important fish stocks
- Recent “discussion” on changing MSFMCA language on what constitutes a recovery plan
- Fish stock **recovery plans** are designed and implemented in an ecosystem context
  - Trophic / community ecology effects
  - **Fish movements, larval dispersal in connected systems**
  - Socio-**economic** considerations (including **fishers**, processors, and cultural factors)

Research questions

- What does an economically optimal recovery plan look like over space and time?
- How do different types of biological dispersal processes affect the dynamics?

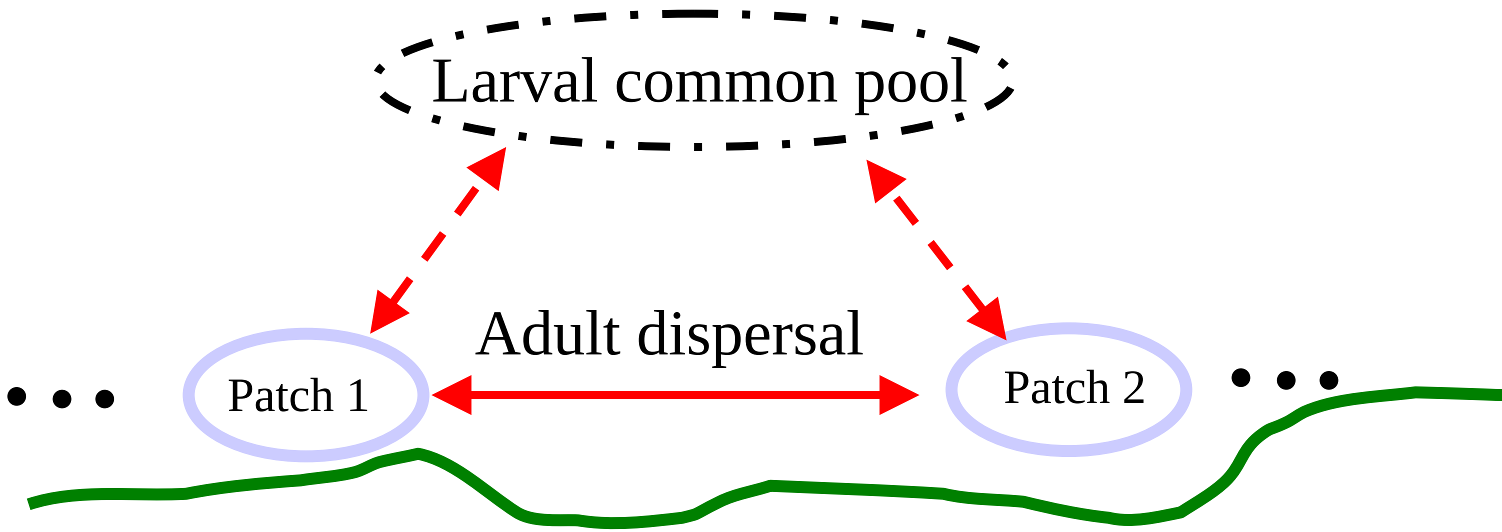
Research methodology

- Develop a spatially-explicit, economic-ecological model of metapopulation
- Numerically calculate the optimal dynamic paths for different sets of initial fish stock levels

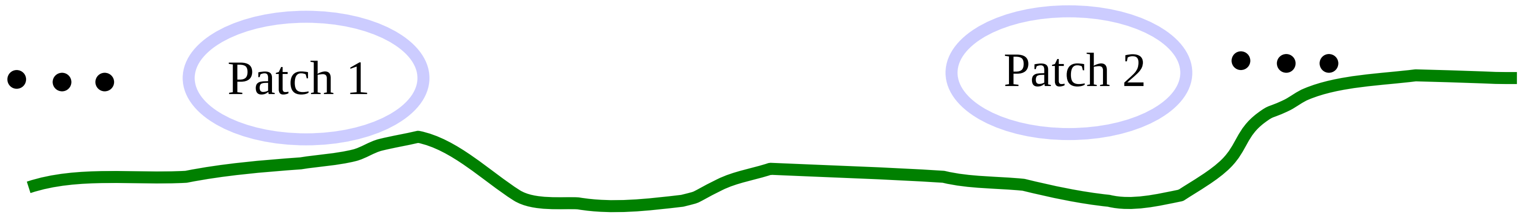
Metapopulation model

- Biomass in each patch has a birth/death process and adult dispersal process, which is driven by relative densities
  - larvae are produced in each patch, mix in a common pool, and then redistribute amongst the patches
- Modify the standard logistic population model

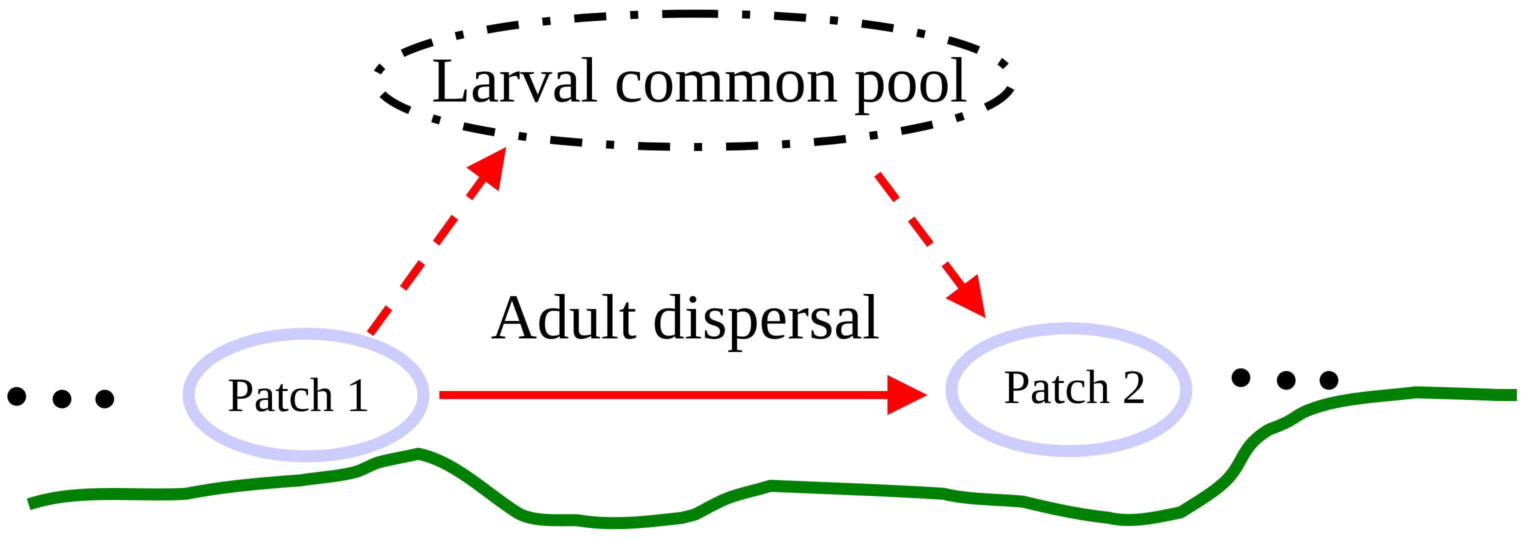
Stylized metapopulation system



Example of isolated (closed) system



Example of source-sink system



Patch 1 is a source, patch 2 is a sink

Model of **isolated** fish populations

$$\frac{dx_1}{dt} = (a_1 x_1 \quad)(1 - \quad x_1) \ - \ h_1$$

$$\frac{dx_2}{dt} = (a_2 x_2 \quad)(1 - \quad x_2) \ - \ h_2$$

- x_i is the population density level in patch i
- a_i is the growth rate in patch i
- h_i is the catch rate in patch i

Model of metapopulation

$$\frac{dx_1}{dt} = (a_1 x_1 \ \ )(1 - \ x_1) + d_{11}x_1 + d_{12}x_2 - h_1$$

$$\frac{dx_2}{dt} = (a_2 x_2 \ \ )(1 - \ x_2) + d_{22}x_2 + d_{21}x_1 - h_2$$

"adult" dispersal process,
which is density independent

Model of metapopulation

$$\frac{dx_1}{dt} = (a_1 x_1 + b_1 x_2)(1 - x_1) + d_{11} x_1 + d_{12} x_2 - h_1$$

$$\frac{dx_2}{dt} = (a_2 x_2 + b_2 x_1)(1 - x_2) + d_{22} x_2 + d_{21} x_1 - h_2$$

“larval” dispersal process,
which is density dependent

“adult” dispersal process,
which is density independent

Connectivity and production

- Biological production in patch 1

$$\frac{dx_1}{dt} = (a_1 x_1 + b_1 x_2)(1 - x_1) + d_{11} x_1 + d_{12} x_2$$

- Contribution of patch 2 on patch 1's production depends on density in patch 1

$$\frac{d}{dx_2}\left(\frac{dx_1}{dt}\right) = b_1(1 - x_1) + d_{12}$$

Optimization framework

- Maximize the present discounted value of profits from fishing in both patches by choosing patch effort levels in each period
  - subject to the metapopulation model, and **a set of initial stock levels**
- Decision-maker is assumed to have perfect information
- Set up as a linear optimal control problem

Fishery profits

- Catch in patch i is $h_i = q_i E_i x_i$
  - E_i is fishing effort in patch i, q_i is the catchability coefficient
- Profits in patch i = $p_i h_i – c_i E_i$
  - Total revenue = $p_i h_i$
    - p_i is the price of fish in patch i
  - Total costs = $c_i E_i$
    - c_i is the spatial cost parameter in patch i
      - costs to fishing can vary spatially due to distance to port, oceanographic conditions, seafloor topology, etc

Infinite horizon optimal control

$$\max_{E_1(t),E_2(t)} \sum_{i=1}^{2} \int_0^\infty e^{-\gamma t} \left(p_i q_i x_i(t) - c_i \right) E_i(t)\, dt$$

subject to

$$\frac{dx_1}{dt} = \left(a_1 x_1 + b_1 x_2 \right)\left(1 - x_1 \right) + d_{12} x_2 - d_{11} x_1 - q_1 E_1 x_1$$

$$\frac{dx_2}{dt} = \left(a_2 x_2 + b_2 x_1 \right)\left(1 - x_2 \right) + d_{21} x_1 - d_{22} x_2 - q_2 E_2 x_2$$

$x_1(0), x_2(0)$ and $E_i^{\min} \le E_i \le E_i^{\max}$

γ is the (social) discount rate

Role (and value) of ecological dispersal

- Unit of biomass that leaves a patch could have been caught there—this represents a cost *today*
- Unit of biomass can, however, be caught in its destination—this represents a benefit *in the future*
- Reallocation of biomass also affects the costs of fishing *in future periods*, as patches that are net sinks (receive more biomass than lose) will have larger population sizes

Role of ecological dispersal (cont.)

- Decision-maker will, therefore, need to make the following trade-off each period for each patch
  - catch more fish in patch 1➔lower population levels, fewer adults and juveniles dispersing to patch 2 vs. catching less fish in patch 1, and maybe more in patch 2
- Trade-off will be determined by relative profitability, which is a function of biological and economic conditions including the initial stock densities, and the nature and strength of the connectivity

Optimal recovery paths

- Start at initial fish stock levels in first period (t=0)
- Find the effort levels in each period (t) to get to the economically optimal equilibrium level
  - Effort levels are chosen to maximize the present discounted value *over* the *entire* time horizon

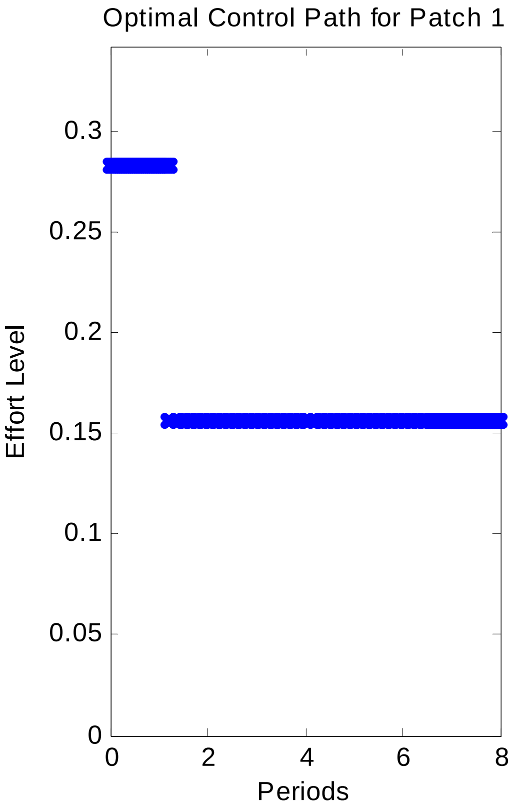
Experiments

- Solve for the recovery path assuming patches are ecologically isolated (independent)
- Investigate how introducing different types of dispersal changes the qualitative nature of the recovery path
  - Focus on source-sink “adult” dynamics with high and low dispersal rates
- Role of the discount rate in a spatial system

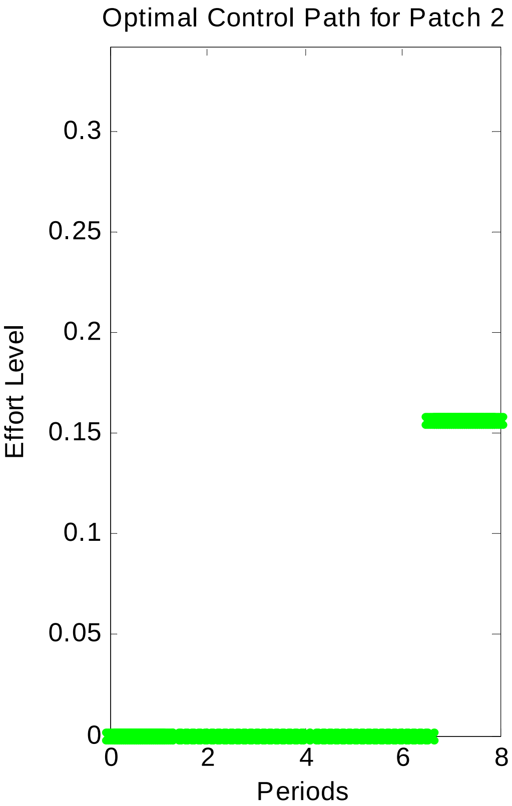
Assumptions

- Only heterogeneity in the system is a 25% cost differential between the two patches
  - Patch 1 is the high cost patch (c1>c2)
- Discount rate of 3%
- Not considering density-dependent dispersal processes (b terms are zero)
- Hold initial conditions constant across the different experiments
  - $X_1(0) > X_1^{ss}$, $X_2(0) << X_2^{ss}$

Two isolated patches: optimal effort levels

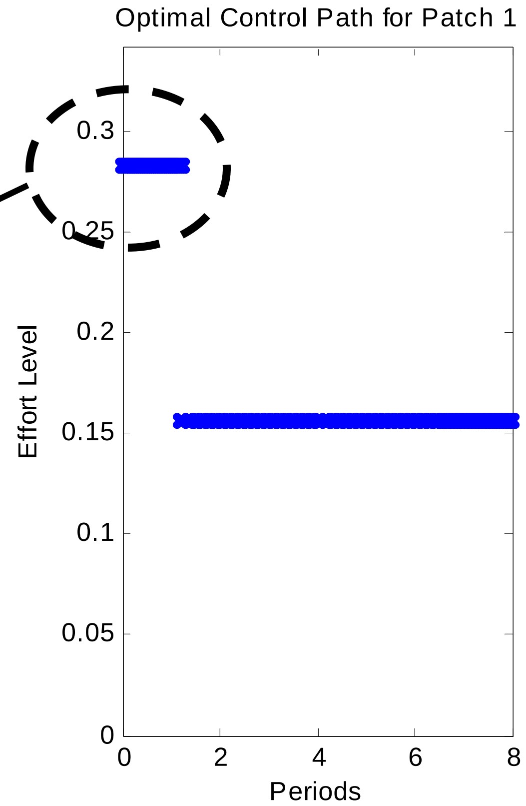


Patch 1



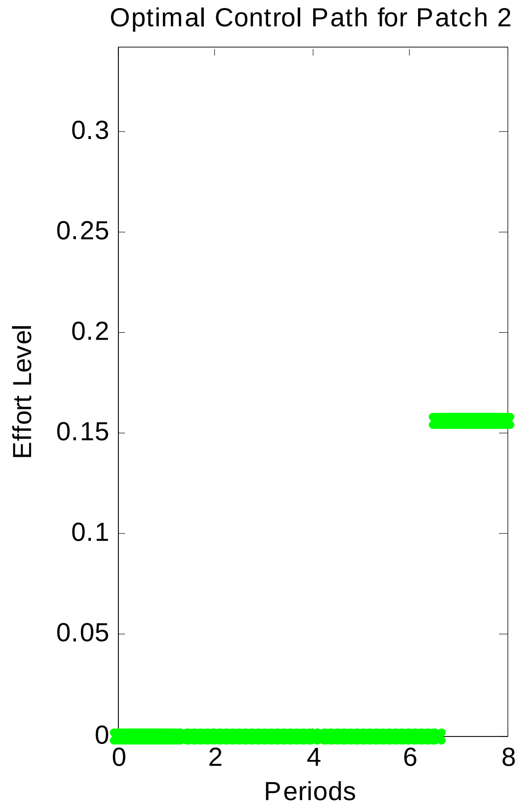
Patch 2

Two isolated patches: optimal effort levels



Fish down the patch with stock above the long-run equilibrium ($X_1(0) > X_1^{ss}$)

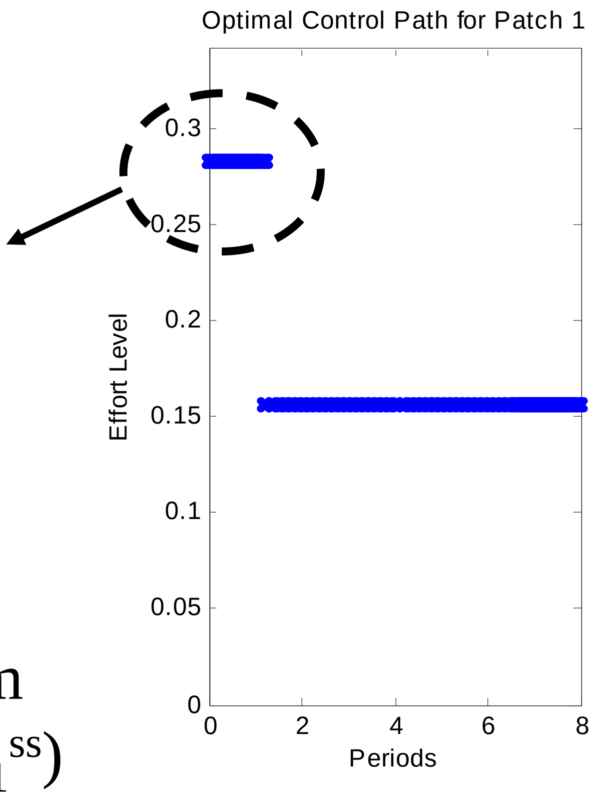
Patch 1

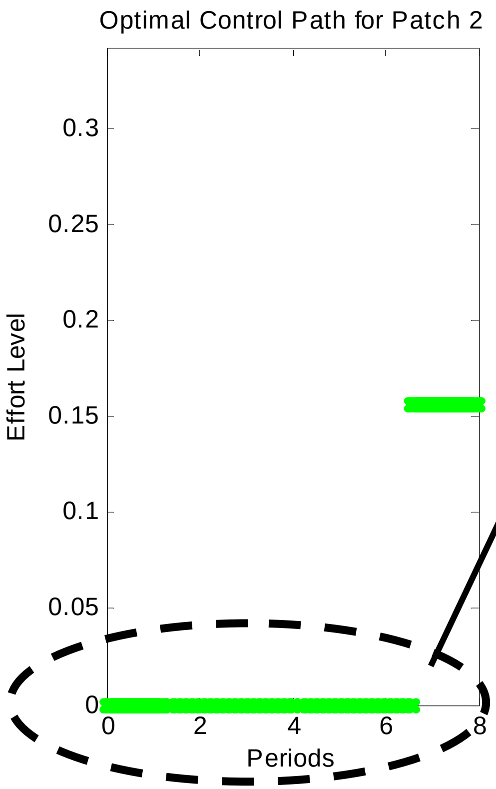


Patch 2

Two independent patches: optimal effort levels

Fish down the patch with stock above the long-run equilibrium ($X_1(0) > X_1^{ss}$)



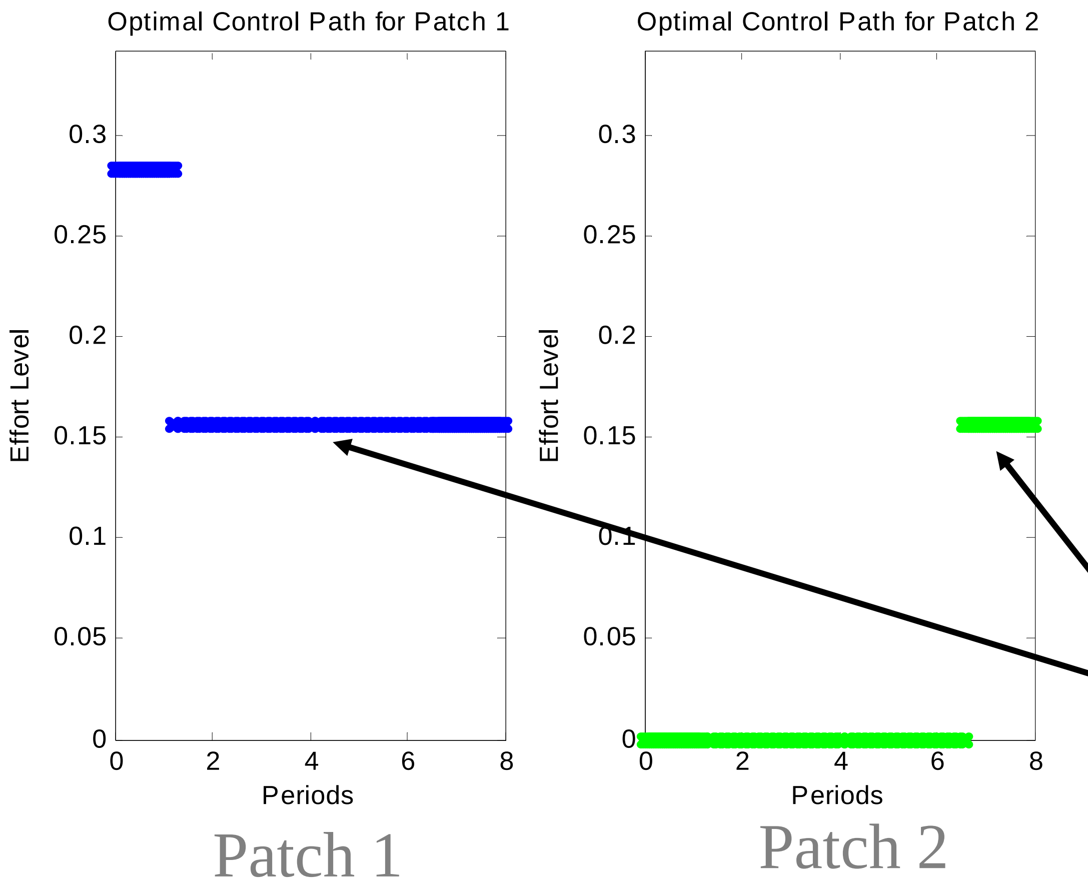


Set effort to zero to rebuild the pop. ($X_2(0) << X_2^{ss}$)

Patch 1

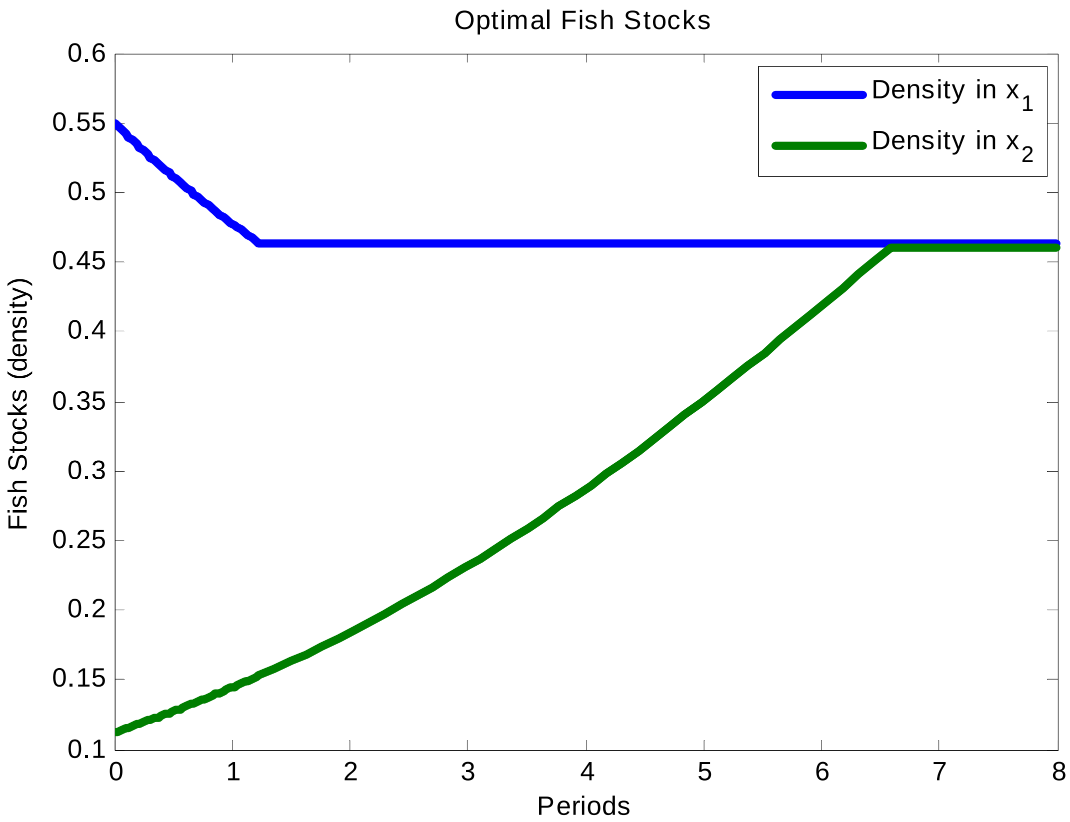
Patch 2

Two isolated patches: optimal effort levels

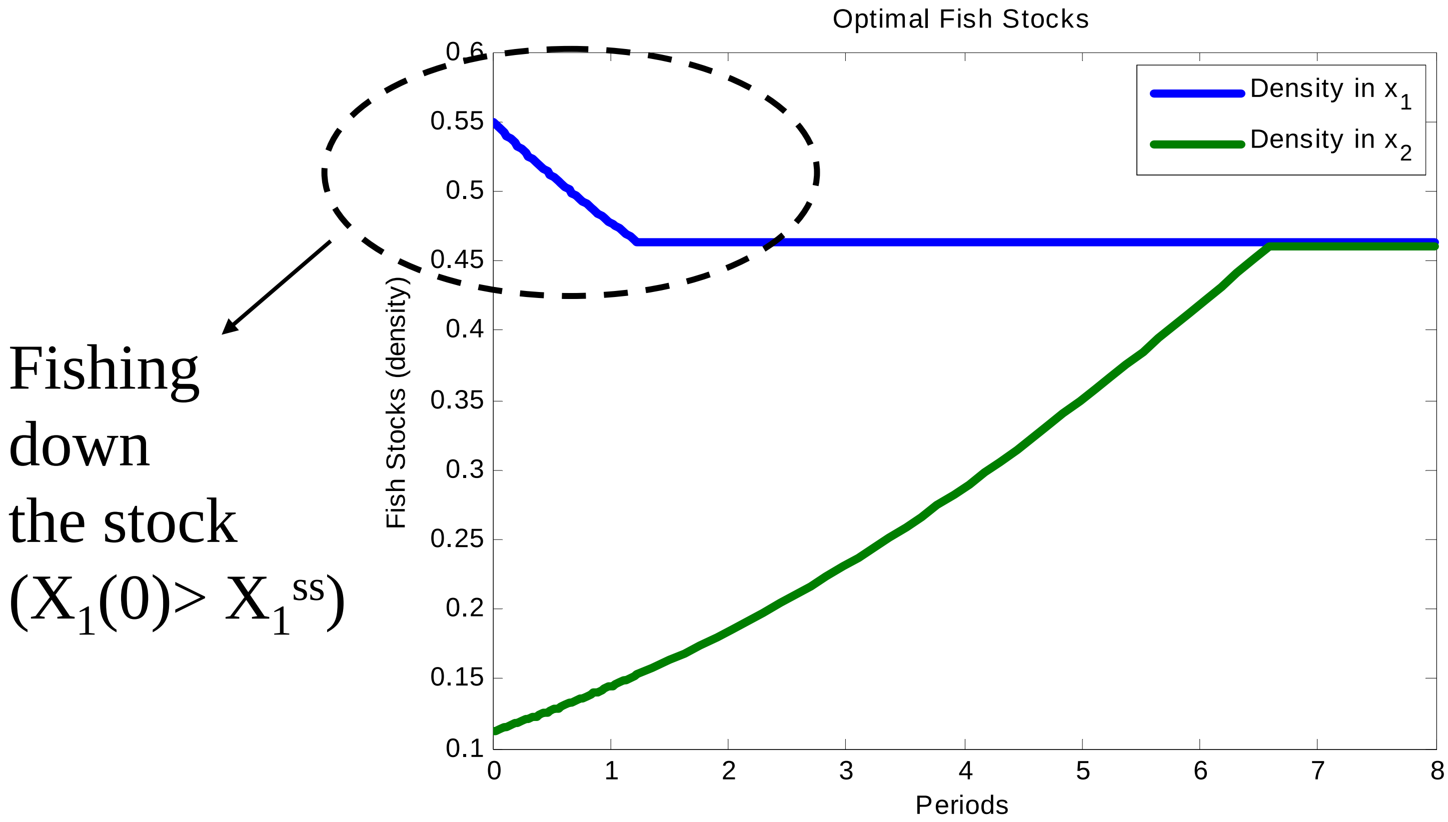


Optimal equilibrium levels of effort in each patch

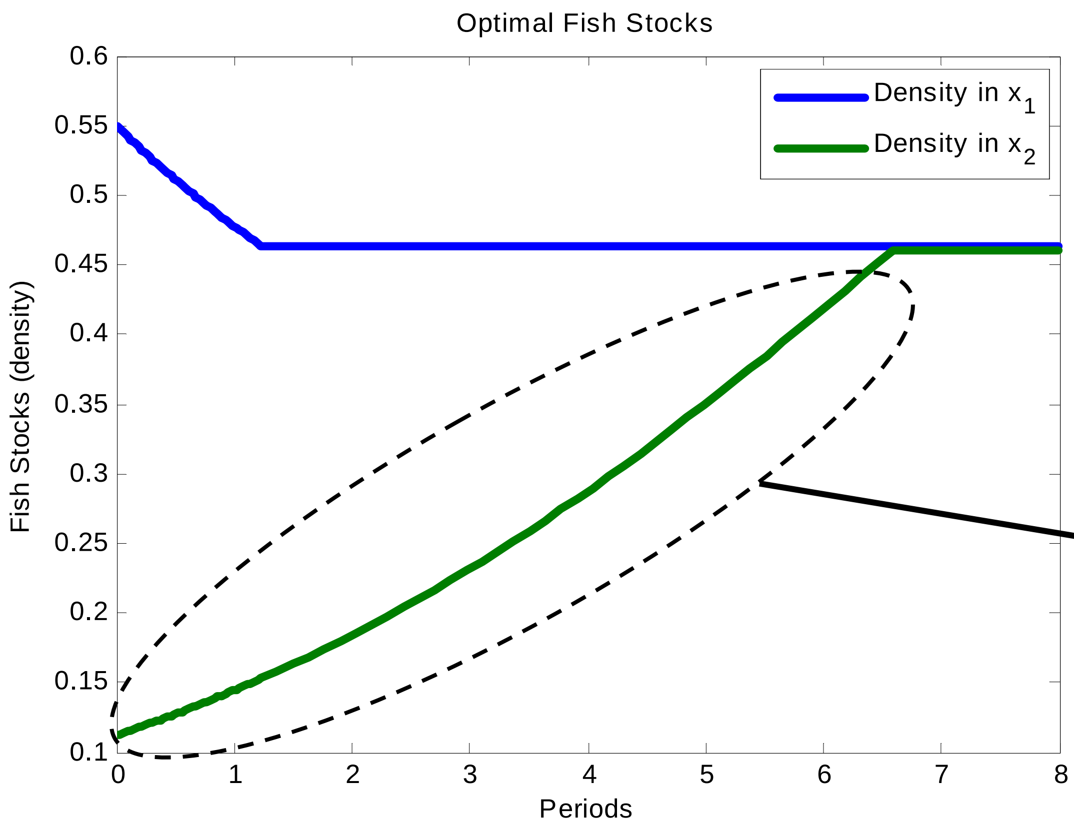
Two isolated patches: optimal fish stocks



Two isolated patches: Optimal fish stocks

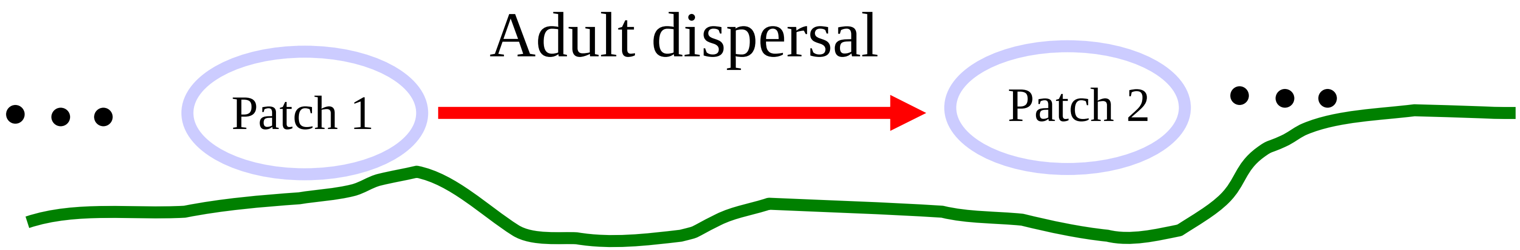


Two isolated patches: Optimal fish stocks



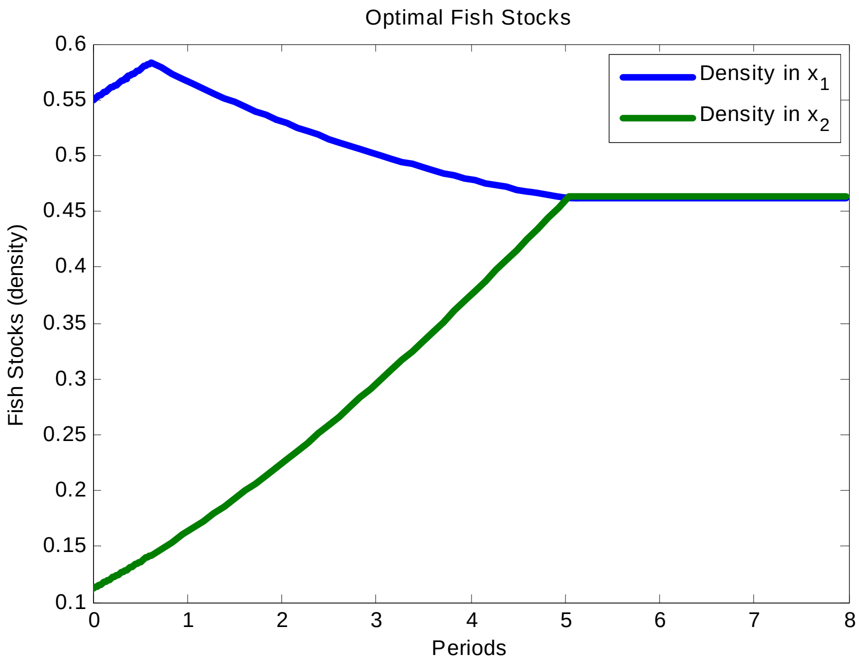
rebuilding the pop. with setting effort to zero ($X_2(0) << X_2^{ss}$)

Introduce dispersal into the system via a source-sink system

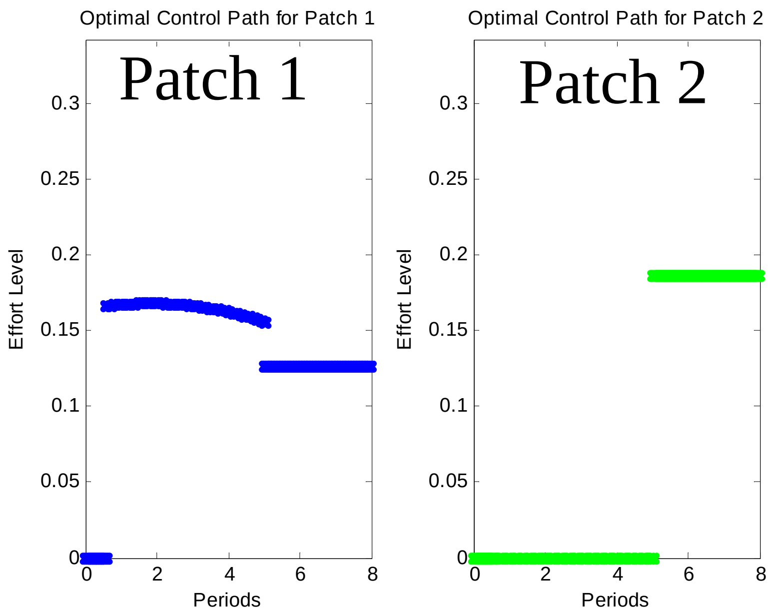


- Investigate differences in dispersal rates (low and high) in this special (limiting) case
- Note two factors determine the flow in any period
  - dispersal rate and population size in patch 1

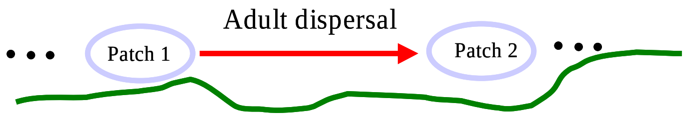
Source-sink with low dispersal rates



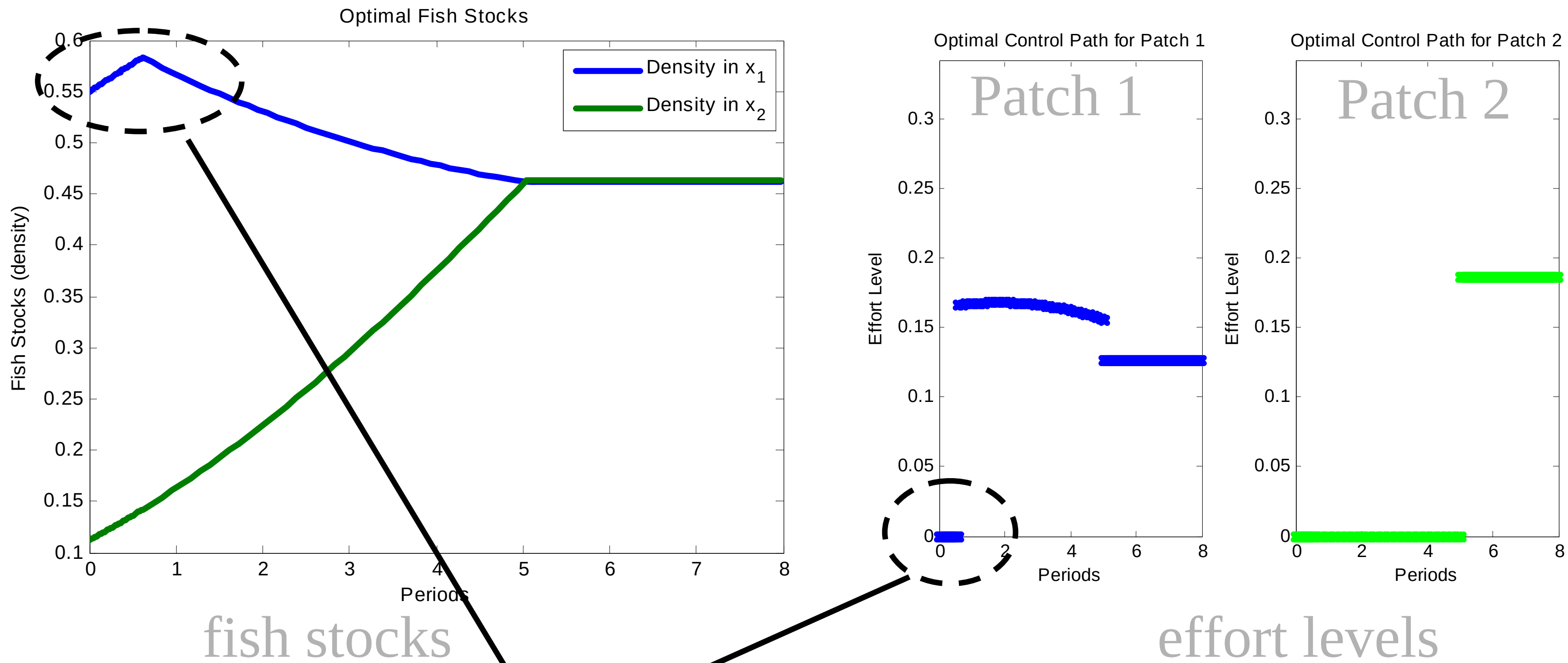
fish stock



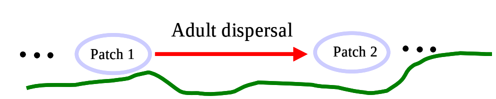
effort levels



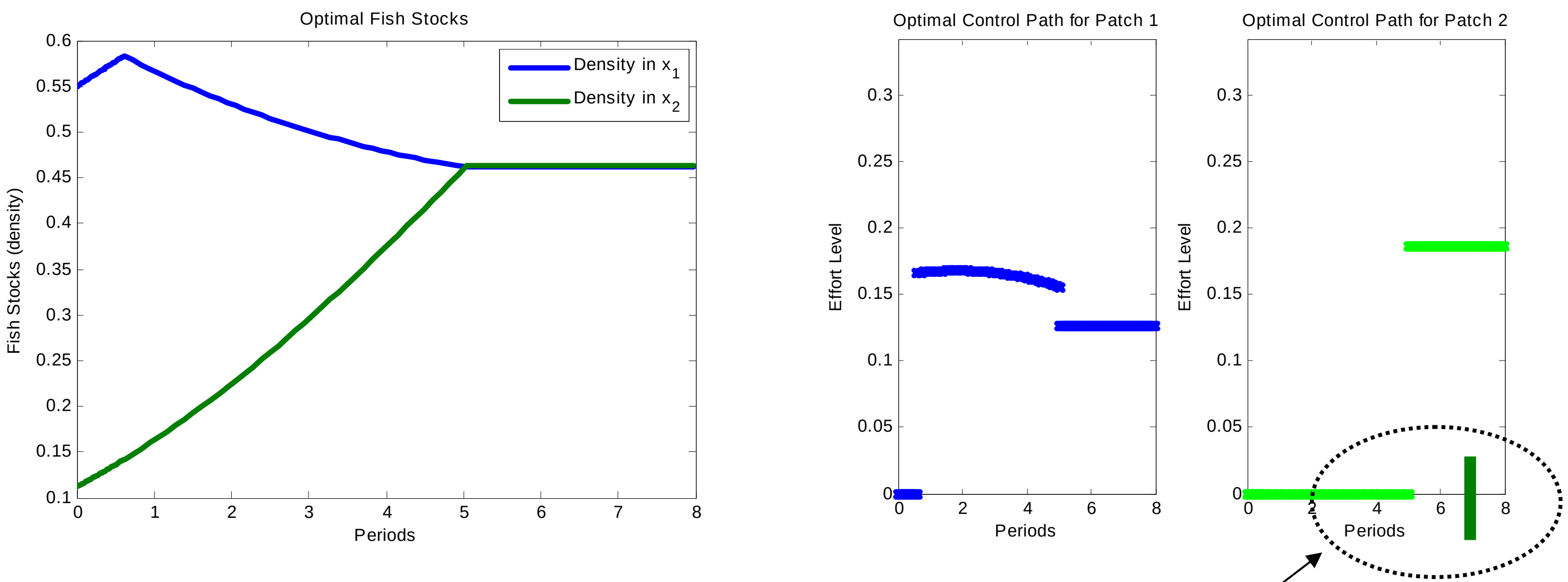
Source-sink with low dispersal rates



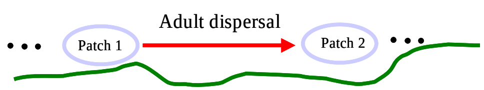
Moratorium in patch 1 ➔ build up the fish stock in patch 1 ➔ more dispersing to patch 2



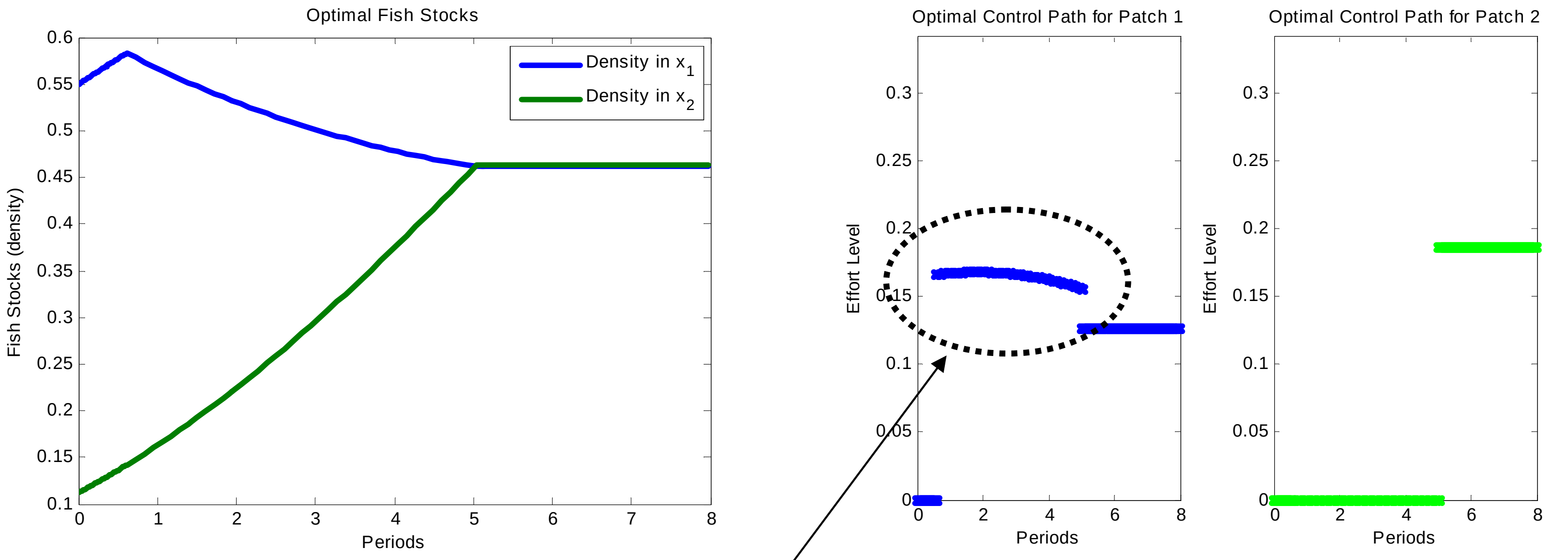
Source-sink with low dispersal rates



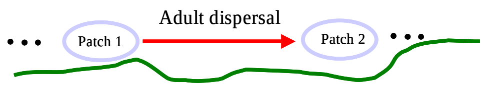
- Moratorium in patch 1 leads to a faster recovery in patch 2
  - shorter moratorium in patch 2 than without dispersal



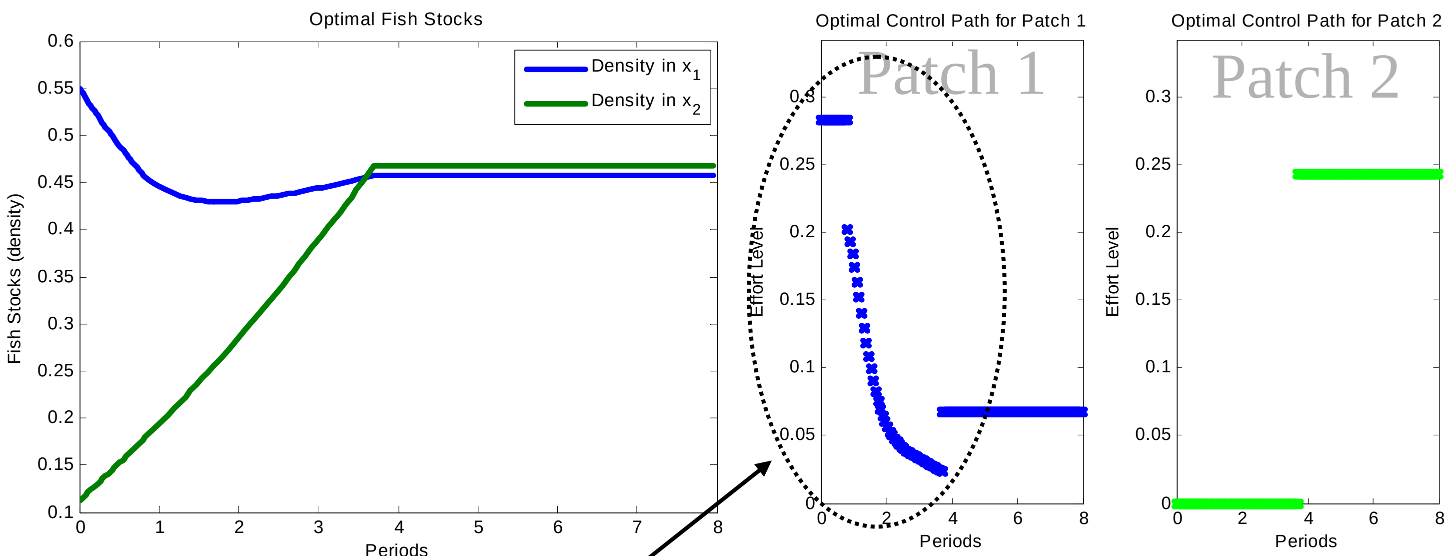
Source-sink with low dispersal rates



- Period where fishing effort in patch 1 is above the long-run equilibrium to drive the population down

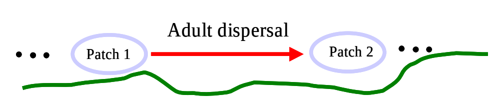


Source-sink with high dispersal rates

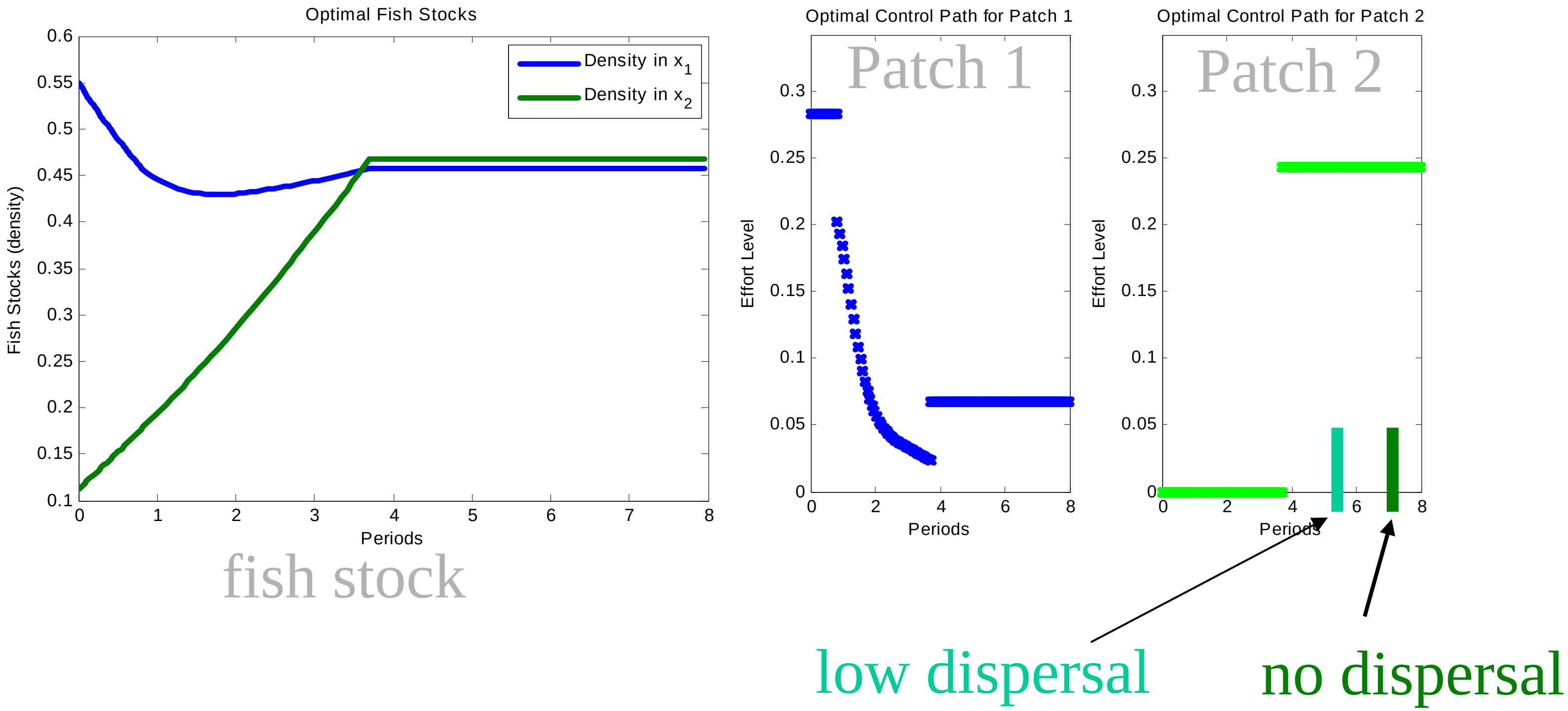


fish stock effort levels

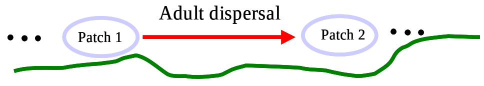
- Why with higher dispersal rates is it no longer optimal to have an initial moratorium?
  - Higher dispersal rates ➔ increase in flow of biomass relative to a lower dispersal rate ➔ a moratorium is not needed to increase the flow of biomass to speed up the recovery in patch 2



Source-sink with high dispersal rates



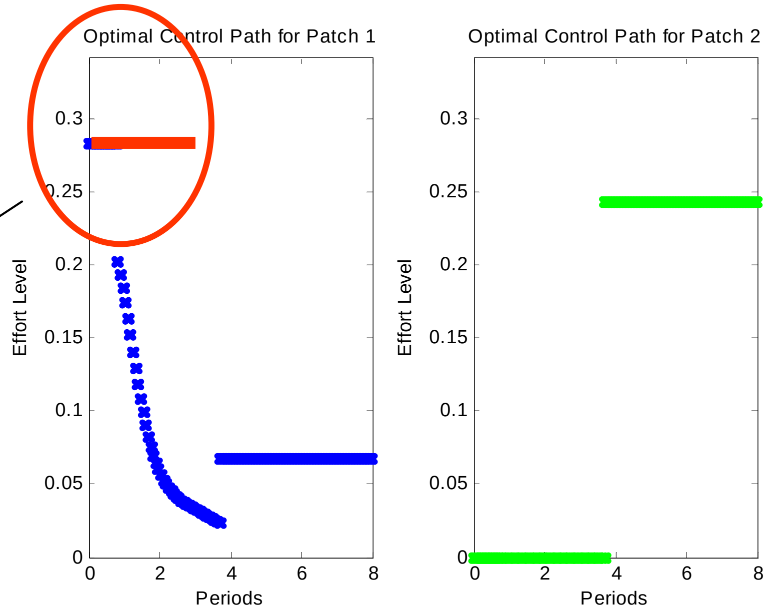
- Moratorium in patch 2 is shorter than before due to the higher dispersal rates



Role of discount rates

- Recall Colin Clark's result that under certain (restrictive) assumptions, if the *discount rate > intrinsic growth rate*, then it is economically optimal to drive the population to extinction.
- Higher discount rates imply greater weight placed on near term net returns

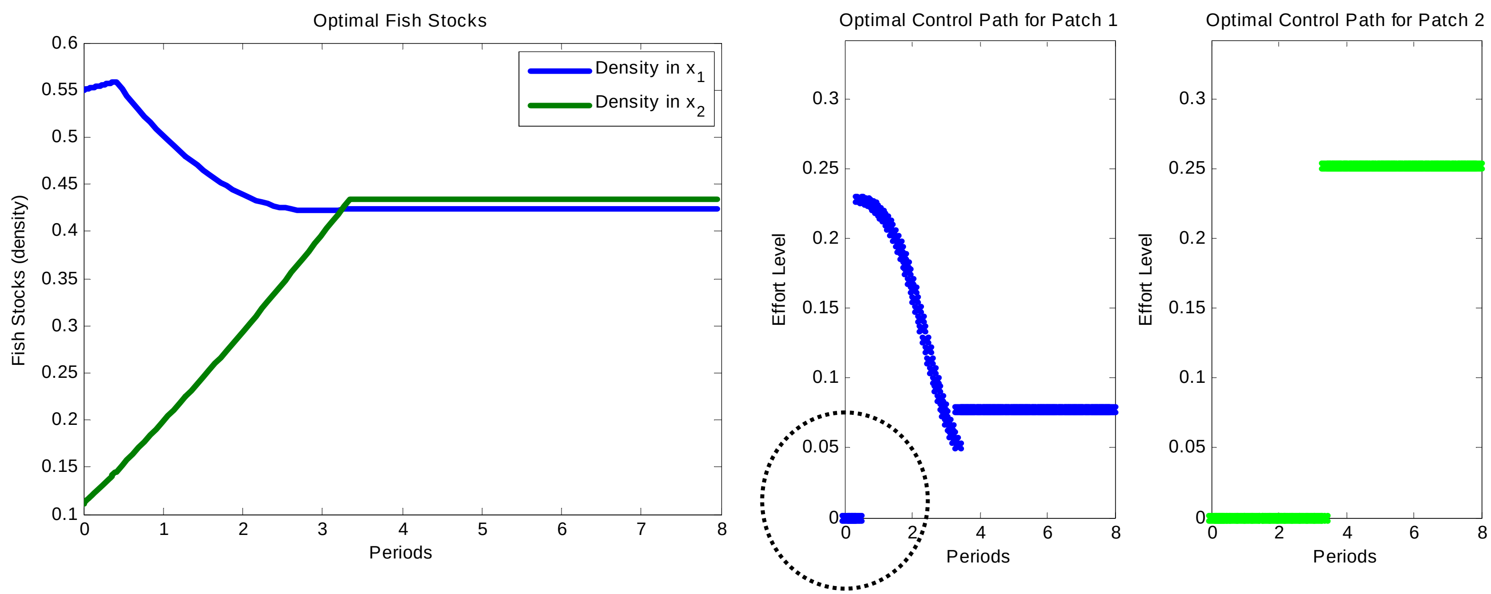
we might expect, therefore,…



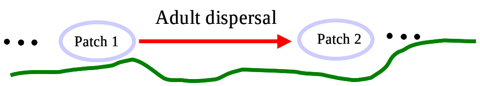
This period to be longer, all else being equal.

You fish patch 1 hard and for a longer period than with a lower discount rate➔ greater returns early on.

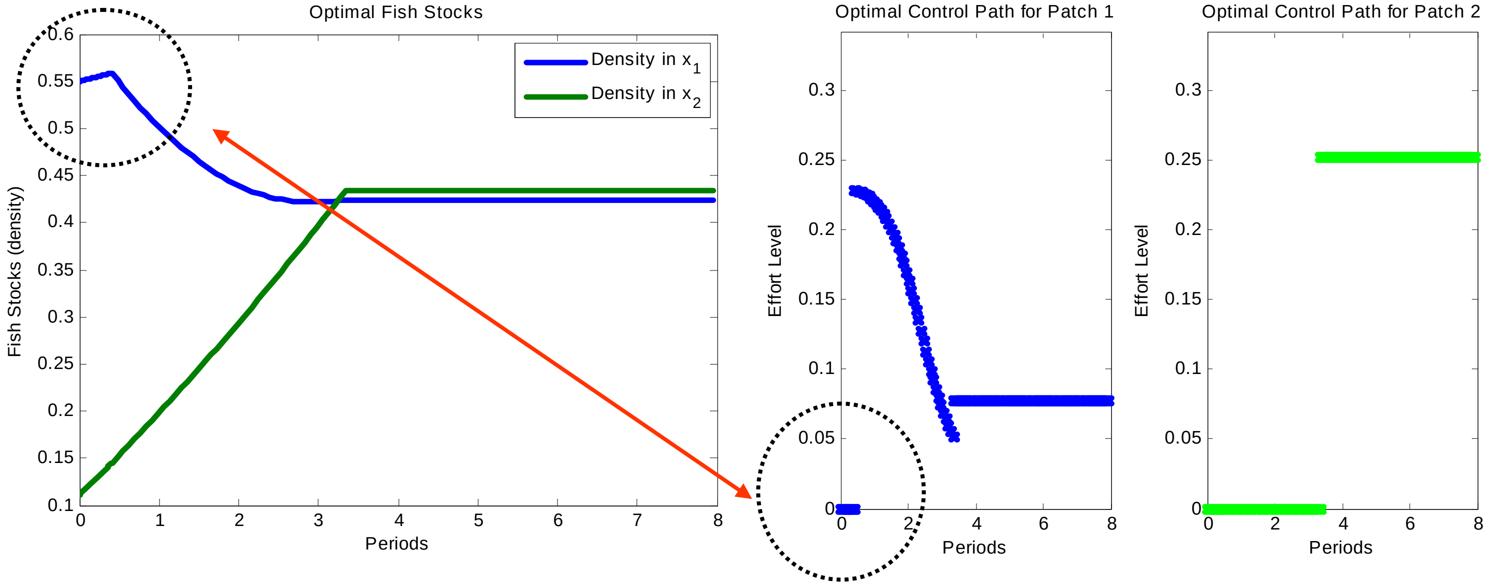
Except, we find the opposite…



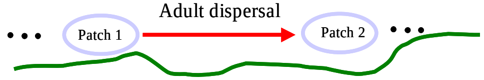
- Why does increasing the discount rate **lead to a moratorium**?



Except, we find the opposite…



- Why does increasing the discount rate **lead to a moratorium**?
  - By closing patch 1, the stock builds up in patch 1, which means more biomass flowing to patch 2



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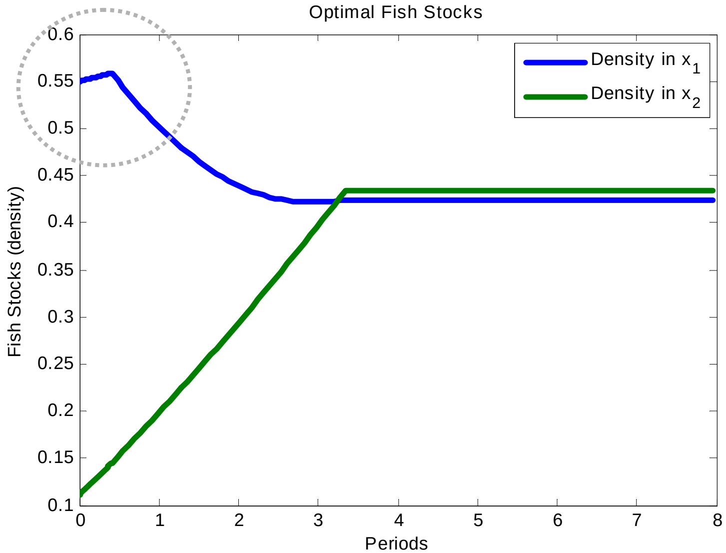
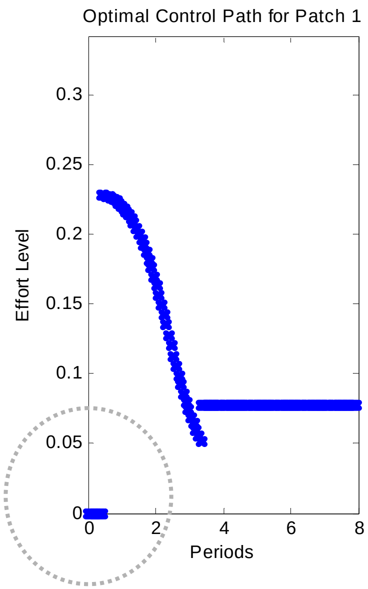
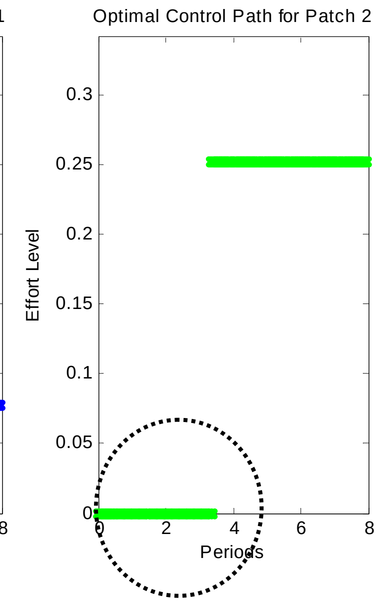
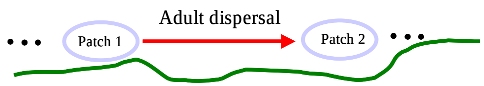






- Why does increasing the discount rate **lead to a moratorium**?
  - By closing patch 1, the stock builds up in patch 1, which means more biomass flowing to patch 2
  - The increased flow from patch 1 to patch 2 results in a faster recovery and a **shorter** moratorium in patch 2 than with the lower discount rate.



Summary of results

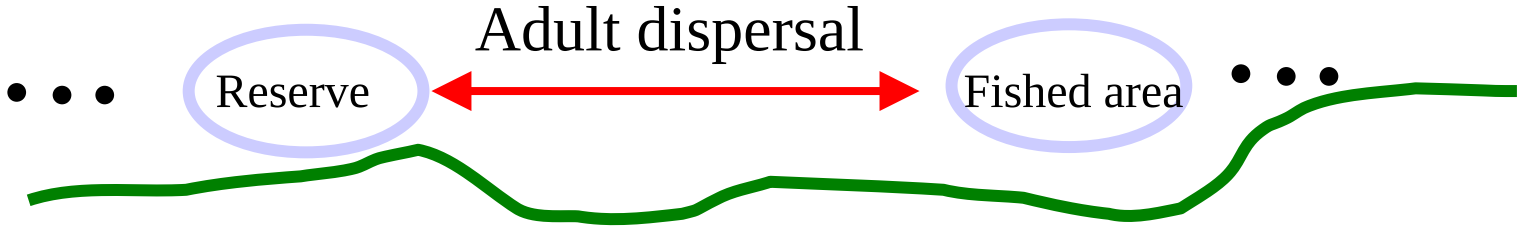
- Optimal recovery paths in a metapopulation are driven by the structure of population connectivity, rates of mixing of populations, and local ecological and economic conditions
- System-wide perspective can lead to counterintuitive results at smaller scales (patches)
  - e.g., discount rates

Areas for further research

- Map out the dynamics in the entire ecological and economic parameter space to understand general patterns
- Understand how many factors in “real” world fisheries management might alter the results
  - e.g., bycatch, multispecies interactions, uncertainties, and in situ values

The end. Thank you.

Net sources/sinks



Type of optimal control problem

- Linear control problem
  - dynamics are bang-bang-singular in nature
- Assume we are at a doubly-singular solution (along both singular paths)
- Investigate the doubly-singular steady-state solution
  - derive equations that implicitly define optimal biomass levels

Adding up (cross-equation) restrictions

- Adult dispersal process: Assume that what leaves a patch arrives in the other patch (no mortality in adult dispersal)
  - $d_{11} + d_{21} = 0$ (recall $d_{11} < 0$)
- Larval process: Larvae either remain in the local patch to settle (a_1) or they go to the other patch and settle (with potential mortality)
  - $a_1 + b_2$£ 1

Optimal steady-state biomass densities

- x_1^* in patch 1 is the solution of

$$\Phi(x_1) \equiv (p_1 - \frac{c_1}{x_1})(\delta - a_1 + 2x_1a_1) - \frac{c_1}{x_1^2}a_1x_1(1 - x_1) = ...$$

$$d_{11}(p_1 - \frac{c_1}{x_1}) + d_{21}(p_2 - \frac{c_2}{x_2}) + \frac{c_1}{x_1^2}(d_{11}x_1 + d_{12}x_2) - ...$$

$$b_1x_2(p_1 - \frac{c_1}{x_1}) + b_2(p_2 - \frac{c_2}{x_2})(1 - x_2) + \frac{c_1}{x_1^2}b_1x_2(1 - x_1)$$

- Terms in blue are due to the local conditions
- Terms in red are due to the spatial processes
- Important to notice that the type of dispersal process affects the level of optimal biomass and catch levels

Optimal biomass levels in <u>isolated</u> populations

- Closed-form solutions exist $(\quad (x_1) \quad 0)$
  - balances value of an instantaneous reduction in stock ***against*** the marginal loss in present value from a long term reduction in steady-state biomass
- Optimal biomass levels are *higher*,
  - the *higher* the cost parameter, c_i
  - the *lower* the price of fish, p_i
  - the *lower* the discount rate, δ

Role of adult dispersal

$$\Phi(\mathrm{x}_1) = d_{11}(p_1 - \frac{c_1}{x_1}) + d_{21}(p_2 - \frac{c_2}{x_2}) + \frac{c_1}{x_1^2}(d_{11}x_1 + d_{12}x_2)$$

- For patch 1, at the margin, optimal solution is balancing
  - loss in marginal profits in patch 1 from fish leaving
  - gain in marginal profits in patch 2 from fish arriving
  - change in marginal costs of fishing due to the reallocation of the fish stock via dispersal

Role of larval dispersal

$$F(x_1) = b_1 x_2 (p_1 - \frac{c_1}{x_1}) + b_2 (p_2 - \frac{c_2}{x_2})(1 - x_2) + \frac{c_1}{x_1^2} b_1 x_2 (1 - x_1)$$

- For patch 1, at the margin, optimal solution is balancing
  - loss in marginal profits in patch 1 from larvae arriving and **<u>competing</u>** with larvae produced and settling in patch 1
  - gain in net sustained profits in patch 2 associated with larvae arriving from patch 1
  - change in marginal costs of fishing due to the reallocation of the fish stock via larval dispersal